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Comparison of biogas development from households and medium and large-scale biogas plants in rural China

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ABSTRACT

As a renewable energy source, biogas not only alleviates energy shortage in rural areas but also effectively reduces the environmental risk associated with agricultural waste management. This study presents a comprehensive overview of development of household bio-digesters and medium and large-scale biogas plants (MLBPs) in China, and discusses the advantages and disadvantages of both biogas systems in terms of environmental performance, role in agriculture, economic benefit, government support, energy efficiency, societal influence, and resident living mode. Both systems have their relative strengths and weaknesses. The operation and maintenance of household bio-digesters are easier, and their environmental and economic performances are superior compared to those of MLBPs. However, MLBPs have higher energy efficiency and better social effect. Thus, the choice of a biogas generation system depends on the local circumstances. Household bio-digesters are suitable for undeveloped regions where the rural residents live far apart from each other, whereas MLBPs are suitable for developed regions where people live close together. The government can play a positive role in preventing the negative impacts of rural social structural change, such as those of urban migration of adults, on household biogas development. Additionally, establishment of scientific and technological support and service systems is recommended for further development of biogas in rural China.

Contents

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1. Introduction

Using non-fossil fuel energy resources, especially renewable energy, has become an important component of sustainable global energy strategy [1]. As of 2012, targets and policies for renewable energy had been established in more than 100 countries, a significant increase from 55 countries in 2005 [2]. Among fossil fuel alternatives, biogas shows great promise as a renewable energy source because it is produced by anaerobic fermentation of household wastes, such as straw, crop stalks, human waste, livestock manure and other organic waste mixtures, and thus provides multiple environmental benefits [3].

As one of the largest agricultural countries in the world, China has abundant biomass resources, including crop straw, firewood, agricultural residues, and organic wastes [4–6]. According to a 2011 estimate by the National Bureau of Statistics of China, about 827 million ton of crop straw and 3.6 billion ton of livestock and poultry manure were produced in China in 2010, and rice straw, corn stalk, and wheat straw accounted for 71.1% of the crop straws produced [7,8] (Figs. 1 and 2). These agricultural residues, if transformed into biogas, can generate 340.8 billion m^3 of biogas, which can address the shortage of energy in rural areas [9]. In addition, effective use of waste biomass can provide significant environmental benefits. Therefore, the Chinese government should put more attention on biogas use in rural areas and provide strong financial support to rural biogas development in order to achieve sustainable development.

Currently, biogas production in rural areas of China comes from two primary sources: household biogas digester, and medium and large-scale biogas plants (MLBPs). Recent years have witnessed promotion of both household biogas digesters and MLBPs [10]. As of 2010, more than 40 million household biogas digesters and 27 thousand MLBPs were being used in rural China, and the number of people benefiting from biogas use had reached 150 million [11]. Rural biogas development in China promotes the construction of a new socialist countryside and improves the environment as well as the quality of rural life. In recent years, the Chinese government has shown increasing preference for MLBPs over household biogas because MLBPs separate livestock farm or energy production from residential areas [12]. Is this preference of government for MLBPs in line with the better performance of MLBPs? Although previous studies have discussed biogas development in China, most have focused on one of these two systems [13–32] (Table 1) or one aspect (e.g., economic assessment, environmental performance, and social preference) of these two systems [33,34]. An overall assessment and comparison of the strengths and weaknesses of both systems is necessary for a comprehensive understanding of biogas development in rural areas of China.

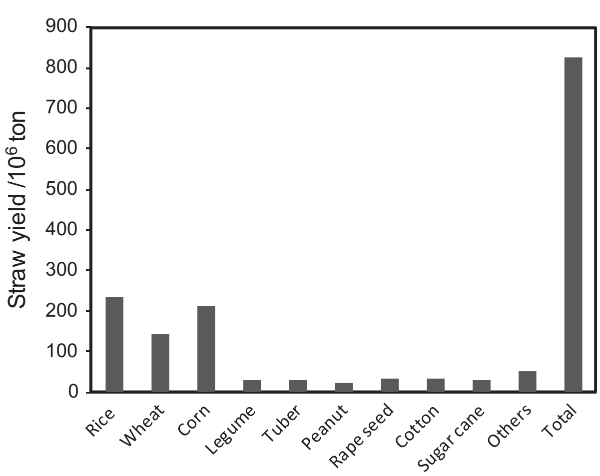

Fig. 1. Crop straw yield in China in 2010 [7].

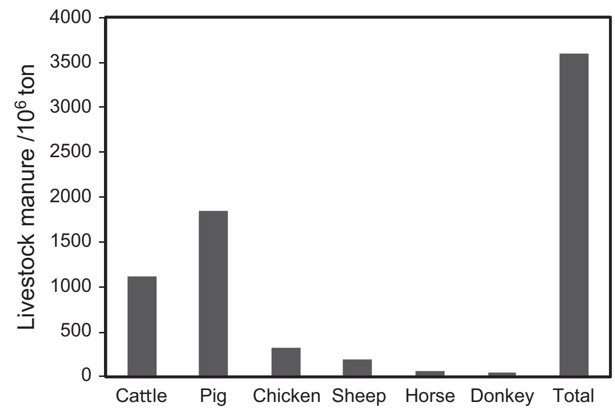

Fig. 2. Livestock manure yield in China in 2010 [8].

Table 1
Studies on biogas development in China.

Biogas model	Corresponding contents	Reference
Household	Ecological and social benefit	[13]
	Environmental performance (CO_2 emission reduction)	[14–16]
	Economic effectiveness	[17,18]
	Policy support and related law	[19–21]
	Energy and emergy analysis	[22–24]
	Available resources for biogas	[4]
	Sustainability effects	[10]
	Bio-digester models	[25]
MLBPs	Biophysical emergy analysis	[26]
	Ecological benefit	[27,28]
	Economic assessment	[29,30]
	Effect of solar energy on biogas production	[31]
	Digestate biological properties	[32]

MLBPs, medium and large biogas plants.

The present study aims to evaluate household biogas and MLBPs in rural China in terms of their strengths and weaknesses by conducting a review of the existing literature. Literature and information on household biogas and MLBPs of China were collected by searching the Web of Knowledge database (http://apps.webofknowledge.com) and China Academic Journal Network Publishing database (http://epub.cnki.net) using the keywords 'biogas', 'household', 'biogas plants', 'biogas project', and 'China'. All relevant government policies, rules, and funding investment were collected from official websites and relevant documents. Data on agriculture straw yields and population distribution were obtained from China Statistical Yearbook. The information collected from these sources was grouped in terms of seven dimensions: environmental performance, role in agriculture, economic benefit, government support, societal influence, energy efficiency, and the resident living mode. The advantages and disadvantages of household and MLBPs are compared side by side within each dimension. The remainder of the study is organized as follows: Section 2 presents a comprehensive overview of development of household biogas and MLBPs in rural China, which is followed by a comparison of the advantages and disadvantages of the two biogas systems in terms of aforementioned dimensions in Section 3. Conclusions and recommendations are formulated in Section 4.

2. Biogas development in rural China

2.1. Biogas development process

China has a long history of biogas use and research, totaling about 90 years. The first time biogas was used in China as renewable energy for lighting was in 1921 as described in a study conducted by Luo [23]. Biogas technology for smallholders in rural areas has significantly improved over the last 40 years with the rapid development of the economy and industries in China. In addition, several standardized and efficient biogas digesters for smallholders have been developed, replacing the water-pressure digester that dominated the market in the mid-20th century. Examples of new designs include the hydraulic cylinder digester, separated floating bell-type digester, meandering stream fabric digester, prefabricated block digester, and spheroidal digester [35,36]. These digesters were designed to use biomass from household sizes of 4–8 persons with a farm production of 2–10 pigs or cattle. In general, household biogas in rural areas spans four development stages and is currently undergoing rapid growth (Table 2). From 1929 to 1942, household biogas was popularized in the country for the first time, and people from 14 provinces benefited from this clean energy. From 1957 to 1978, biogas was given increasing attention by the scientific community because of the negative effects imposed by rural energy shortage, traditional use of biomass fuels, and severe deforestation; this period marks the second wave of household biogas promotion. However, given the limitations of technology at the time, several biogas digesters built during this period suffered from gas leakage problems, which led to failure in household biogas expansion in the 1970s. The 1990s witnessed the rebirth of biogas development as a part of a strategy for establishing new rural socialism and sustainable agriculture in the 21st century. From 2000 to 2010, construction of household biogas digesters entered a sustained and rapid growth stage under the support of government policies, with more than 1 million units built each year and an annual average growth rate of about 15% [11] (Fig. 3). It has been estimated that the total household biogas yield was 12.4 billion m^3 by the end of 2009, equivalent to 19.0 million t of standard coal [37]. Household biogas has undoubtedly become the biggest biomass energy industry in China.

Smallholder farming gradually decreased during the process of agricultural industrialization, and an increasing number of large-scale farms were constructed in rural China. Several medium and large-scale livestock and poultry farms are mainly located in residential areas and close to water sources. Discharge of waste from these farms can cause significant environmental problems [38]. Thus, establishment of MLBPs became an increasingly favored measure to tackle the challenge of preventing pollution from livestock manure discharge. Biogas plants in China began their operation and production in the 1950s and have been characterized by stable and healthy development throughout their 50-year development. In the middle 1990s, with the rapid development of scale livestock breeding, the number of biogas plants increased rapidly (Fig. 3). According to a 2010 estimate from the Rural Energy Industry Association of China, about 27,000 MLBPs that annually produced 1.01×10^9 m^3 of biogas were in existence by the end of 2010.

2.2. Circular agricultural models for biogas in China

Circular agriculture is an agricultural operating mode that rationally allocates and utilizes agricultural resources and energies, maintains environmental capacities, and readjusts agricultural economy system in accordance with ecological laws [39,40]. It is also a mode of development that helps to realize the ecological transformation and the economic increase of agriculture, and is thus an important and effective means that implements the strategies for sustainable development of agriculture [41]. In addition, it supports the following “the optimal resource–production–products–reproduced resources” loop for the purpose of reducing agricultural resources and energies, reusing products and recycling refuse for the development of agricultural economy [42,43]. Finally, a circular agricultural economy supports the motto of “the most suitable exploitation, the best production, the most favorable consumption, and the least refuse”. With the development of ecological engineering since the 1980s, different circular agricultural models for biogas system have been applied to the local circumstances in China [44–47]. Biogas-linked agrosystem has become an important route to promote agricultural structure adjustment and enhance renewable energy utilization in rural China [23]. In the biogas-linked agrosystem, the incorporation of anaerobic digestion into the complex agrosystem presents advantages over traditional agricultural practices and waste handling procedures in at least three ways: firstly, the substrate for anaerobic digestion is from various agriculture wastes, which

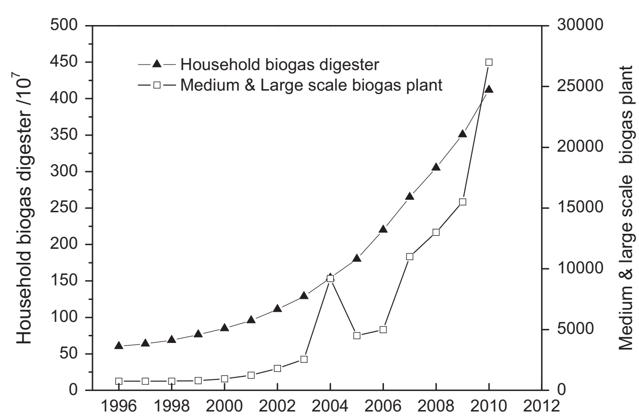

Fig. 3. The development of household biogas and medium and large-scale biogas plant in China from 1996 to 2010 [11].

Table 2
The process of biogas development in China.

Year	Biogas development remarks
1921	Luo Guorui firstly used water-pressure digester for biogas production for lighting
1921–1942	The first rapid development stage in China, the biogas technology training was begun
1958–1970	The second rapid development stage in China, specialized biogas research institutes established
1970–1990	The third rapid development stage in China, strategy of new rural socialism and sustainable agriculture was launched by Chinese government
2000–2010	The new, steady and sustainable stage. More policies was proposed by Chinese government including “Biologically Enrichment of the Countryside Project” in 2000, “Rural Household Biogas State Debt Project” in 2003, “Renewable Energy Law” in 2005, “Project of Rural Biogas Project” in 2007, “Act on the Development of Circular Economy” in 2008

reduce environmental pollution resulting from the wastes being burnt or directly dumped into the field; secondly, it produces a comparatively clean high methane fuel for electricity or heating; thirdly, the residue of biogas fermentation can be effectively used as organic fertilizer for agriculture [48]. This is how the concept of "circular" for biogas utilization can be updated: emphasis should be placed not only on the lower emission resulting from use of cleaner fuel, but also the benefit of indirect emission and pollution reduction from the great degree of circulation of materials and energy flows in a closed input–output system [23]. Thus, due to their significant environmental and economical advantages, circular agricultural patterns and models that are suited for biogas production from households and biogas plants have been implemented in China.

2.2.1. Household biogas digester

Three models of household biogas are employed in rural China: the "three-in-one," "four-in-one," and "five-in-one" circular agricultural models.

The first circular agricultural model, called the "pig-biogas-fruit" pattern, is widely used in southern China and consists of a biogas digester combined with a pigpen and toilet [49]. In this model, biogas from livestock manure and human excrement can be used as fuel for lighting, heating, and cooking while biogas residue can be used as fertilizer for growing fruit trees and vegetables. The typical digester volume is 8–10 m^3, which produces between 0.1 and 0.3 m^3 of gases per m^3 of digester volume per day [50]. Thus, green products can be obtained from this model, and the rural environment can be protected by efficiently using wastes.

The "four-in-one" circular agricultural model, which combines a biogas digester with a pigpen, greenhouse, and toilet, is popular in northern China [25]. Biogas digesters can operate well in the range of 8–60 °C, but northern China is cold in the winter with conditions that are unsuitable for biogas generation. Therefore, this model necessitates the effective transformation of solar energy through biotechnology. The greenhouse is highly important in this model in that it increases temperature and allows for a more suitable environment for biogas production. The generated biogas can then be used for greenhouse heating, which allows vegetables and animals in the greenhouse to grow and thrive [51].

The "five-in-one" model combines a biogas digester with a solar-powered pigpen, water cellar, rain-water collecting pool, and a suite of drip irrigation system. It is designed for arid and semi-arid regions in northwest China [52]. In this ecological model, the water cellar supplies water for orchard irrigation through the drip irrigation system, as well as for anaerobic fermentation. This model enables energy reuse, water-saving irrigation, environmental protection, and improvement of standards of rural living [53,54]. Rebuilding and connecting a new toilet to the biogas digester is a key component of household biogas digester development because the spread of disease caused by mosquito breeding can be eliminated.

2.2.2. MLBPs

MLBPs are a part of the circular agriculture model and always come with medium- or large-scale livestock farms. The role of MLBPs in the circular agricultural model is to extend the food chain and facilitate the reuse of agro-resources to realize the multilevel utilization of energy [55]. Both energy approach and ecology approach are employed in MLBPs.

The energy approach aims to use livestock manure as organic fertilizer after anaerobic fermentation. Household biogas circular agricultural models can be applied to the biogas plants in this approach. The most common pattern is cow–biogas–pasture, in which livestock manure is used to produce biogas through anaerobic fermentation. Then, biogas is used as energy for biogas plant heating so that a certain reactor temperature can be maintained and residues can be converted to organic fertilizer [56,57]. If the scale is sufficiently large and biogas production is abundant, biogas can also supplied to households or used to generate electricity. This approach presents significant economic benefits while making full use of the discharges of organic waste treatment. However, it is suitable only for locations where sufficient croplands or fish ponds are available for post-treatment [30].

The ecology approach aims to improve the quality of discharges of livestock manure after anaerobic fermentation. In this approach, livestock manure and wastewater are separated into slurry and solid waste [58] (Fig. 4). After being dried, the solid waste is used as organic manure, and the liquid is then passed to the digester for anaerobic treatment and aerobic post-treatment. This is done for compliance with the national standards for wastewater effluent discharge, which is meant for water used for irrigation purposes [30]. Thus, a stabilization basin for liquid aerobic treatment is necessary, which makes for higher installation and operational costs in this model.

3. Comparison of household biogas and MLBPs

3.1. Environmental performance

Household biogas can provide clean renewable energy and reduce greenhouse gas (GHG) emissions. Biogas is the direct product of anaerobic digestion (AD) and can be used as fuel for cooking, lighting, and heating. Utilization of biogas can effectively reduce the per capita fuel consumption in rural families by partly replacing coal, oil, fuelwood, straw, and livestock manure, among

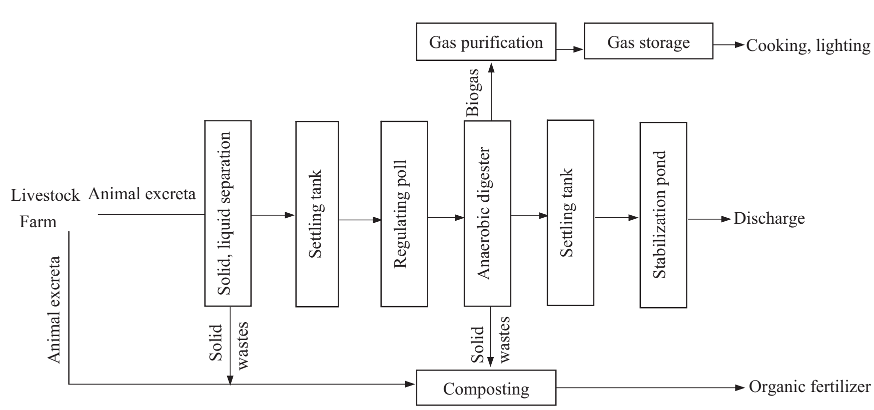

Fig. 4. Ecology approach of circular agriculture model of a biogas plant [45].

others [18,59]. Moreover, biogas utilization has been reported to be a very important pathway to global GHG mitigation [60,61]. Liu et al. [62] reported that a 10 m^3 rural household-scale biogas digester can reduce over 1.517 t CO_2 per year compared with coal combustion. Gosen et al. [10] also reported a great reduction in GHG emission by household biogas digester per year. According to the Agricultural Ministry of China, 12.4 billion m^3 of biogas produced by the end of 2009 equaled to 19.0 million t of standard coal (equivalent to the annual storage of 0.11 billion acres of forestland) and reduced more than 45.0 million t CO_2 emission [37]. Similar to household biogas, MLBPs can generate biogas as fuel for heating and contribute to GHG emission reduction. However, due to the distance between large-scale farms and villages, biogas use is always restricted to farms to avoid the high costs of biogas pipeline networks [63]. Large digesters provide large amounts of renewable energy and digestates to a community. However, due to the large size of biogas plants, technology and management skills must be available to ensure the efficient distribution of digestates to the neighborhood.

In addition, household biogas can improve environmental sanitation by reducing non-point source (NPS) pollution and recycling resources in rural areas. Rural environmental problems in China are serious because the management and treatment of agricultural waste, animal manure, and emissions of straw burning to the atmosphere are not regulated by a national standard. Several studies conducted abroad show that NPS is an important issue in environmental water pollution, with agricultural NPS posing the greatest risk [64–66]. Three of the major types of agricultural NPS pollution include loss of nutrients, pesticides, and soil and water. Thus, the control of NPS pollution is key to water pollution control [67]. Livestock and poultry manure are rich in total nitrogen and phosphorus, and the lack of relevant legislation allows poultry wastewater to be discharged without decontamination, which results in serious agricultural NPS pollution. China produces 4 billion t of agricultural wastes every year, including 2.61 billion t of livestock manure and 0.7 billion t of crop stocks (accounting for 83% of the total agricultural wastes). In addition, the number of household breeders accounted for 73% of the total animal manure produced [68], which means that full use of household wastes (animal manure and crop straw) can substantially lower agricultural NPS pollution. In a household biogas circular model, human excreta and livestock manure can also be fully used for biogas generation. According to the Agricultural Ministry of China, during a comprehensive consideration of fermentation raw materials, climate, and social economy, 148 million rural families, which are about 59.27% of the total, were found to be suitable for household biogas development [69]. Therefore, the development of household biogas will not only provide a clean and renewable energy source but also reduce pollution caused by discharges of livestock and poultry manure without decontamination and emissions from crop straw burning.

The main difference between biogas from MLBPs and that from households in terms of agro-ecology is that MLBPs play important roles in point-source pollution. Medium and large-scale biogas plants can treat large amounts of manure produced by large-scale livestock and poultry farms, as well as municipal and industrial organic waste streams. However, with the development of agricultural technologies and the increasing amount of chemical fertilizer and pesticide use in rural China, the proportion of NPS pollution has increased annually and become a primary threat to watershed environmental health. Therefore, the main pollution problem of rural environments in China is NPS pollution rather than point-source pollution [64]. Investigations on eutrophication in Dianchi Lake indicate that the total nitrogen (TN) and total phosphorus (TP) generated by NPS pollution comprise 44.5% and 26.7%, respectively, of the total pollution load [70]. Unlike point-source pollution, NPS pollution is characterized by random and intermittent occurrence, complex mechanisms and processes, uncertain discharge channels and amounts, variable spatial and temporal pollution loads, and difficulties in monitoring, simulation, and control [71]. These characteristics lead to inconveniences when monitoring, controlling, and treating NPS pollution. Therefore, from the point of view of NPS control, household biogas is the key to realize both biomass reuse and rural environment improvement.

Furthermore, the resultant slurry after anaerobic fermentation can be directly used as fertilizer, thereby decreasing the impact on environmental pollution. Given that the scale of MLBPs is too large to enable direct management of slurry, investing in biogas residue is necessary. Slurry treatment facilities are especially important in preventing secondary pollution, unless there is a cropland or pond nearby. However, because the costs of waste treatment are exorbitant and slurry treatment facilities require a large area, many users of medium scale biogas equipment do not treat their discharge wastewater. As a result, secondary pollution is rampant in MLBPs and is a primary constraint to their widespread adoption. Therefore, in terms of contribution to secondary pollution, household biogas is more eco-friendly than MLBPs.

3.2. Role in agriculture

Household biogas can provide organic fertilizer for agriculture. Digestate, the residue of biogas fermentation, is a high quality organic fertilizer and an effective pesticide. Most pathogenic organisms in the raw materials (e.g., livestock and poultry or human excreta) are killed during the anaerobic process [72]. The solid part of digestates can be used as organic fertilizer after the separation of solid and liquid. Tan [73] reported that the conversion rate of ammonium nitrogen after using digestate for co-digestion (crop straw and animal manure) could reach 163.3%, which is 1.25 times higher than that for compost. The physical properties of soil are improved after long-term application of biogas residues, and the organic matter, nitrogen, phosphorus, potassium, and other nutrient contents of soil, as well as soil enzyme activity [48], increase more when treated with organic fertilizer than with chemical fertilizer (Table 3). The liquid of digestates, called the anaerobic digestion slurry (ADS), is an efficient and clean insectifuge. ADS presents strong reducibility due to its low oxidation–reduction potential during the anaerobic process and exhibits physiological roles of deoxidation and degreasing once in contact with pests [72]. Pesticide loss is another important form of NPS pollution in rural China. In a household biogas circular agricultural model, ADS can be used in orchards, vegetable fields, and croplands, thereby reducing the need for pesticides and chemical fertilizers. Using ADS thus aids in agricultural NPS pollution control. MLBPs can also provide fertilizer and pesticides to farmers, but unlike those from household digesters, the sludge from MLBPs

Table 3
Effects of different fertilizers on soil properties [41].

Treatment	Organic matter ($g\ kg^{-1}$)	Total N ($g\ kg^{-1}$)	Total P ($g\ kg^{-1}$)	Total K ($g\ kg^{-1}$)	Bulk density ($g\ cm^{-3}$)	Porosity %	Total salt ($g\ kg^{-1}$)
Inorganic fertilizer	27.9	1.27	2.35	25.3	1.28	53.1	2.36
Manure fertilizer	36.7	1.79	4.23	25.5	1.13	58.6	1.73

are commonly sold to farmers with greenhouses, and are thus not readily available to all farmers [12].

3.3. Economic performance

The economic performance of bio-digesters is an important factor for local farmers who consider bio-digester as an investment. Household biogas system construction usually includes two components: a biogas reactor and “three changes” that represent an improved kitchen with a biogas cooker, improved pigpen, and new toilet connected to the reactor. The volume of household biogas digesters is commonly only 8 m^3. The costs of household biogas system consist of digester installation costs and operational costs. The installation cost covers the materials used for bio-digester construction, such as cement, bricks, sand, and PVC planks. The operational cost includes material supplies, manure and sludge transportation, and sludge removal from the bio-digester for further use. The material supplies for digestion is freely available for farmers' breeding animals. However, construction costs vary due to differences in reactor types and costs of materials and labor. The potential income sources are related to fuel substitution and fertilizer and pesticide substitution because biogas use would save money on coal and liquid petroleum gas, and the use of sludge would either save money or increase the productivity and revenue from crops [74]. In the most rural areas of China, over half of the investment for a household bio-digester comes from central and local governments; farmers just pay the technician costs, labor costs and material transportation fees. A typical farmer's income is usually enough to cover these expenses.

MLBPs must have an integrated pretreatment system, comprehensive biogas slurry utilization, or post-treatment and biogas refinery storage and transport systems. The cost of biogas plant construction ranges from 10 thousand to 10 million CNY (Chinese Yuan), which is equivalent to US$ 1.54 thousand to 1.54 million, including the investment on equipment and pipelines, installation, manure/biomass handling and transportation, water and desulphurizing reagents, and labor and maintenance [58]. Besides, China has established an Environmental Impact Assessment System and the Three Simultaneous Systems to promote environmental protection, wherein the laws stipulate that construction projects must undergo an environmental impact assessment and that environmental protection facilities must be designed, constructed, and implemented at the same time as construction projects [75]. Therefore, investment on waste treatment facilities is an important part of the cost of biogas plants. The potential income of MLBPs relates to the sale of biogas and the sale of sludge as fertilizers.

Clearly, the construction costs incurred from MLBPs are considerably higher compared with those from household biogas. Although the government subsidizes a part of these costs, owners of biogas plants still pay high costs, which is a great burden for many plant owners. Furthermore, the total costs of producing gas outweighs the benefits of most MLBPs in rural China because of the huge investment involved [10]. On the other hand, household digesters typically bring significant economic benefit due to their lower investment requirements. For instance, He et al. [12] investigated the bioenergy systems of 12 villages in the Shandong province of China and estimated the average total costs of household biogas to be 0.44 CNY $\cdot$ m^{-3} of gas and the average revenue to be 0.52 CNY $\cdot$ m^{-3} of gas, while the average total cost of MLBPs was estimated to be 1.16 CNY $\cdot$ m^{-3} of gas, and the average income was 0.47 CNY $\cdot$ m^{-3} of gas. Thus, the cost of producing gas in MLBPs significantly outweighs the benefits. Therefore, from an economic point of view, household digesters may be profitable than MLBPs.

3.4. Government support

Biogas is a widely available energy resource in China, and the central government strongly supports the development and application of biogas energy. To this end, the central government has formulated a series of policies and programs to promote the development of biogas energy [19,33].

The Chinese government issued the Renewable Energy Law and Renewable Energy Prices and Cost-sharing Management Trial Procedures in 2005 to encourage various domestic enterprises to become involved in renewable energy development [76]. In the same year, promotion of rural biogas development was definitively proposed in the PRC law on Agricultural, Energy Conservation, Renewable Energy, and Animal Industry Act and included in the 21st Century Agenda and National Guidelines on Medium- and Long-Term Program for National Economic and Social Development of China. In October 2005, the government made exploitation of renewable energy a priority and accordingly, the program for rural biogas development was included in the Eleventh Five-Year Plan and Twelfth Five-Year Plan of the Chinese Ministry of Agriculture [69]. In February 7, 2006, the National Development and Reform Committee issued Regulations Related to Renewable Energy Power Generation in support of the Renewable Energy Law, which oversaw the approval of renewable energy projects and management of power they generated. The regulations also provided guidance for the implementation of standards for enterprises entering the renewable energy industry [77]. In 2007, the Chinese government published the Medium- and Long-term Development Program for Renewable Energy. On 1 April 2010, a revised Renewable Energy Law became effective, which stipulated that the State would implement a fully supported system for managing the power generated by renewable energy [78].

Aside from energy policies, the Chinese government also created a series of economic measures to promote the development of biogas energy. For instance, the revised Renewable Energy Law stipulated a renewable energy development fund in 2005, which consisted of a special fund and an additional renewable energy surcharge of 0.002 CNY per kWh in the sale price of power. This fund provides financial support to power-generating plants through the provision of a premium price for the power originating from renewable energy sources [78]. In September 2007, China announced its plans to invest 2 trillion CNY (US$ 0.33 trillion) towards the completion of renewable energy development by 2020 to lessen pollution from coal burning and achieve cleaner growth. Furthermore, the government offered financial loans for the construction of household biogas digester and medium- and large-scale biogas plants in rural areas [19]. Thus, both public policies and legal measures have been instated in China to provide stable and long-term support to rural biogas development.

It is also notable that establishing household biogas digester is strongly supported both financially and strategically by central and local governments of China. Since 2001, government funding has been increased at both central and local government scales. Financial subsidies from the central government vary across the country (east to west); 800–1000 CNY (US$ 123–154) is offered to peasant families intending to build household biogas facilities [79]. The subsidy is mainly used for purchasing building materials, biogas stoves, and technicians' salaries. This means that the peasant family pays only a small proportion of biogas construction costs, which they can pay through credit loans with interest subsidy financed by the local government. To further encourage commercial banks to actively participate in biogas technology promotion, funding for loan guarantees has been provided by some governments and international funding agencies.

The central government has also provided subsidies for the promotion of development of biogas plants in rural China.

From 2001 to 2005, the central government invested 81.15 million CNY (US$ 12.5 million) in building 850 medium- and large-scale biogas plants for large livestock and poultry farms. According to China's Rural Biogas Project Program (2007), from 2006 to 2010, 6000 more biogas plants were to be built, and the number of biogas plants would increase to 30,000, accounting for 39% of the total livestock and poultry farms [69]. Financial subsidies from the central government also vary across the country. From the east to the west, 0.7–1.3 million CNY (US$ 0.1–0.2 million) are allocated for biogas plant construction. The local governments are also required to provide additional subsidies [80]. According to the "National Debt Project for the Rural Biogas Construction", the total investment by the central government to the rural biogas industry from 2002 to the end of 2010 reached over 20.0 billion CNY (Fig. 5), of which about 82% went to the construction of household biogas digesters, about 10% went to the construction of medium- and large-scale biogas plants, and about 8% financed service systems. Thus, it is clear that significant investments have been made and specific policies have been implemented by both central and local governments for the development of household biogas and MLBPs.

3.5. Societal influence

The Chinese government has been promoting the construction of household biogas plants in rural China for decades. The traditional agricultural structure in China is characterized by household agriculture in which farmers do both the planting and the breeding. In this structure, a rural family owns some pigs or cows that provide abundant raw materials for biogas production in order to meet the energy demands of cooking, heating and lighting. However, changes in the social structure have gradually affected rural household biogas development. As the largest and fastest developing country in the world, the rapid economic development and industrialization of China has increased urbanization rapidly since the economic reform and opening of the country in 1980. It is estimated that during the past 30 years, the proportion of urban population has increased from 19.4% in 1980 to 49.9% in 2010 [7] (Fig. 6), and this trend will continue in the next 20 years. According to a forecast by the United Nations, almost 350 million Chinese will be migrating to urban areas in 2030 and the urban population will reach 68.7% [81]. An increasing number of young rural residents moving into cities and become migrant workers have resulted in the elderly and children remaining in rural areas. However, these family members do not have the ability or energy to build biogas digesters.

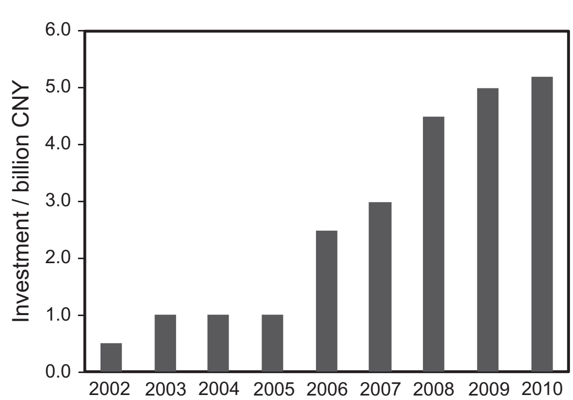

Fig. 5. Funding support from China government on the biogas industry from 2002 to 2010 [35].

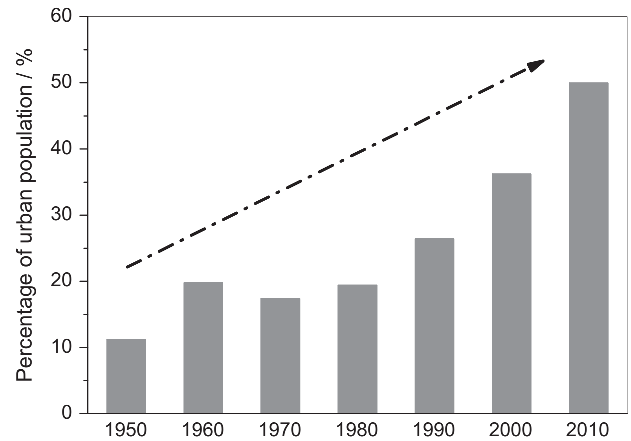

Fig. 6. Dynamic of urban population in China from 1950 to 2010 [7].

Compared with household biogas digesters, the operation and management of MLBPs can create jobs for farmers and reduce their housework load and maintenance work. With the establishment of the new socialist countryside, scattering of feed is gradually being replaced by intensive livestock farming. This has resulted in a trend in which livestock farms are separate from plantations. Central disposal of wastes at such farms imposes harmful effects on the environment. Manure from intensive livestock farms provides abundant raw materials for anaerobic fermentation. Therefore, biogas generation through MLBPs can help in protecting the rural environment However, changes in the rural social structure is necessary to facilitate the development of MLBPs.

China is a large agricultural country and half of its population (671 million) is considered rural, based on 2010 figures [7]. Although the urbanization rate of China rose to 49.9% in 2010 [7], this rate is still low compared with 70% in the US. Changes in the agricultural social structure in rural areas have constrained household biogas development, but it is an irreplaceable and effective approach to addressing energy shortage and environmental problems. The government could implement new policies in the New Socialist Countryside Construction initiative to eliminate impediments to household biogas development.

3.6. Energy efficiency and supply capacity

Biogas digesters work over a certain temperature range, and the minimum temperature for biogas production is around 10 °C, with the rate of production increasing with increased temperature [82]. A typical household biogas digester in rural China is a concrete construction submerged in the soil to ensure constant temperature, but lacks any way of measuring and adjusting the operating temperature and mixing the digestate. The temperature of these biogas digesters is close to the ambient air temperature in winter, which causes low biogas production efficiency. Local farmers have to resort to coal stoves to heat their rooms in the winter. This is a serious problem in the northern region of China where the daily mean temperature in winter is usually below 10 °C. In general, the yearly window with temperatures permitting acceptable level of biogas production is about 5–8 months in northern China, 7–9 months in central China, and 10–12 months in southern China [83]. MBLPs are not affected by temperature and can consistently generate large amounts of renewable bioenergy due to the use of standardized and advanced engineering equipments and materials such as heaters, stirrers, monitors and fibre-reinforced plastic.

3.7. Rural resident living mode

Apart from the environmental performance, economic benefit, policy support, social effect, and energy efficiency, the living mode of rural residents should be taken into account when choosing biogas systems. In China, the unbalanced economic development between western and eastern regions has led to significant differences in the quality of rural living. For instance, in the Xinjiang province, which covers 1.66 million square kilometers and lies in western China, the rural population size is 22.30 million. This means less than 14 people inhabit per square kilometer in this region [7]. In other western regions such as Qinghai, Tibet and Gansu provinces, rural poulation density is even lower with less than 8 people per square kilometer. In such conditions, the three phases of raw material collection, biogas production, and biogas supply are decentralized. There is no need to concentrate livestock and poultry manure and crop straw from every single household to a certain site, and they are used on a household-by-household basis. If biogas projects are built in a centralized way, pipelines must be laid down between the big project and the households. Due to the fact that the peasants live far apart from each other, long pipelines would have to be built individual households, resulting in higher cost. Furthermore, compared with MLBPs that consist of complex components and operation and maintenance by professional workers, household biogas systems have a simple structure that farmers can easily manage on their own. Therefore, household biogas is more suitable than MLBPs in regions where residents live far apart from each other.

In contrast to the undeveloped western part of China with a vast territory and sparse population, eastern China is characterized by its small size and large population. For example, in well-developed regions such as Guangdong and Zhejiang provinces, people live in close proximity and the population density is over 600 per square kilometer [7]. Because of this, the apportioned costs of building pipelines and gas stations for individual customers are quite low. The infrastructures to collect and concentrate rubbish and manure in these regions are also good, so centralized medium- to large-scale plants are suitable for biogas generation in these regions.

4. Conclusions and recommendations

The rapid economic growth of China has led to substantial increase in energy consumption. Reducing dependency on fossil fuels through the development of sustainable energy sources is very important for sustainable economic development of the country. Biogas production through anaerobic fermentation of agricultural wastes is a promising method alternative to fossil fuels. The present study discussed the development process and current status of biogas production in rural China. Biogas production from households and MLBPs was compared in terms of environmental performance, role in agriculture, economic benefit, government support, societal influence, energy efficiency, and resident living mode (Table 4). In general, both systems have their relative strengths and weaknesses. The operation and maintenance of household bio-digesters are easier, and their environmental and economic performances are superior compared to those of MLBPs. However, MLBPs have higher energy efficiency and better social effect. Thus, the choice of household bio-digesters vs. MLBPs depends on local circumstances. Household bio-digesters are suitable for undeveloped regions where rural residents live far apart from each other, whereas MLBPs are suitable for developed regions where people live close together. The government should understand such regional differences, choose the appropriate biogas model, and allocate resources accordingly for rural biogas development. Furthermore, the government could play a positive role in preventing the negative impacts of rural social structural change, such as those of rapid urban migration of adults, on household biogas development.

Table 4
Comparison of household biogas digester and medium and large-scale biogas plant.

Items	Household biogas digester	Medium and large-scale biogas plant
Environment performance	Better	Good
GHG emission reduction	Good	Good
Solution of pollution	Non-point source	Point source
Digestion slurry pollution	Inexistence	Existence
Residue for agriculture fertilizer	Better	Good (just for farmers with greenhouses)
Economic performance	Profitable	Not profitable
Government support	Strong	Strong
Societal influence	Not create job	Create job, and reduce the workload
Energy efficiency	Relatively low	Relatively high
Operation and maintenance	Relatively simple	Relatively complex and professional required
Suitable for regions	Western rural areas	Eastern rural areas

To further develop the biogas industry in rural China, the authors recommend that scientific and technological support be strengthened to promote household biogas development in rural areas, especially for smallholder biogas digesters in cold regions where biogas production rate is low during winter. The process of changing from scattered feeding to intensive livestock farming will lead to the lack of raw material for household biogas. The use of crop straw or a mixture of straw and manure as a raw material could be a solution to this problem. As difficulties in the biological hydrolysis of lignocellulosic biomass limit the use of crop straw, relevant studies, such as determination of the optimal carbon to nitrogen ratio for co-digestion, effect of pretreatment of crop straw and the role of microbes in the fermentation process, are necessary for improvements in fermentation technology. The authors also recommend that local governments in China support biogas production by creating a service system for household biogas digester building, improvement, maintenance, and technical guidance. Urbanization increases the number of young farmers moving to cities and the population remaining in rural areas often has limited ability to build digesters. Professional teams should be established in order to make up for the shortage of manpower and to provide long-term technical help to rural residents. Financial support for biogas development should support not only the construction of digesters but also the end use of biogas products to solve problems regarding secondary pollution of MLBPs. Models of comprehensive utilization of biogas must also be promoted through successful demonstration of projects with measures adjusted to local conditions.

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